Development of Self Compacting Concrete (SCC) by using High Volume of Calcareous Fly Ash

I. Papayianni[1], **E. Anastasiou**[1]

[1]Aristotle University of Thessaloniki, Aristotle University Campus, 54124, Thessaloniki, Greece

KEYWORDS: self compacting concrete, calcareous fly ash, mechanical characteristics, early shrinkage deformations

ABSTRACT

Rheological and mechanical properties as well as long term volume stability seem to be the target characteristics in developing SCC for concrete applications. Calcareous fly ash as mineral admixture in concrete mixtures often increases water demand for a required consistency. This does not favor the proportioning of SCC with this fly ash since viscous mixtures of low mobility are produced. However, calcareous fly ash exhibits noticeable self-cementing capacity and could replace a high volume of Portland cement. In this experimental work, a calcareous fly ash replaced cement in different proportions up to 50% by mass and the effects on rheological properties and mechanical characteristics were measured, as well as shrinkage deformations. All necessary modifications in proportioning and mixing are also mentioned. Based on the results, the production of SCC of adequate 28-day strength (50 MPa) with high volume calcareous fly ash can be achieved.

INTRODUCTION

A well known practice for optimizing Self-Compacting Concrete (SCC), which is characterized by the high volume of cementitious paste, the high consistency and passing ability with resistance to segregation and bleeding [1], is the use of mineral admixtures such as fly ash, which often replaces around 35% of cement clinker. This alternative is cost-effective, provided that fly ash is a locally available low-cost by-product, it contributes to the reduction of emissions and enhances consistency at low water-cementitious materials ratio (w/cm) of SCC [2].

In many areas such as Greece the available fly ash emanates from the burning of lignite, is of high calcium content and may be characterized as ASTM class C or as calcareous fly ash according to EN 197. It could be said that although these fly ashes constitute more than half of the total fly ash production in Europe, their exploitation is much less compared to that of siliceous type fly ashes, according to the ECOBA statistics [3]. This is attributed to problems related to their homogenization, their free lime and sulfate contents, as well as to the excess of calcium aluminate compounds when high-calcium fly ashes are used in combination with cement in concrete production. However, their abundancy as well as the potential for upgrading their quality provides a strong motive for their beneficial utilization in concrete production, since they contribute to early strength development more than siliceous fly ashes, due to their self-cementing hydraulic character. In Greece, there is a long-term experience in using calcareous fly ash in blended cement production and in infrastructure projects such as grouting and roller compacted concrete production [4], while its use in concrete production is covered by a National Standard [5].

The studies on the use of calcareous fly ash in SCC are very limited. This lack of interest could be attributed to the particular behavior of calcareous fly ash in concrete mixtures. For example, calcareous fly ashes often increase water demand which seems to be a negative effect for SCC proportioning. However, as research has proven, there are ways to overcome such problems and have technical advantages from calcareous fly ash incorporation into the cementitious material of SCC. In this paper, calcareous fly ash (HCFA) was used for 30% and 50% wt. of cement replacement in SCC mixtures. Basic properties of fresh and hardened SCC were measured in order to determine if the addition of high volume of HCFA in the cementitious material may render a SCC of sufficient quality.

SCC mixtures develop higher shrinkage deformation and present greater cracking tendency especially at early stages (called autogenous and plastic shrinkage) compared to ordinary concrete mixtures [6]. In this paper, the effect of calcareous fly ash on early shrinkage development was also measured. According to the literature [7], plastic shrinkage occurs when evaporation exceeds the rate of bleeding in a fresh mixture until its hardening. In addition, autogenous shrinkage takes place independently of external forces and evaporation and is confronted with difficulty in SCC. In order to mitigate early shrinkage and cracking tendency, different fiber types, expansive agents [8] and shrinkage-reducing admixtures (SRAs) [9], as well as internal curing [10] have been used. Among the expansive agents used, CaO-based and calcium sulfoaluminate-based agents have been advantageously used to compensate early deformation of concrete mixtures.

The calcareous fly ash produced in Greece is a very low-priced by-product that possesses self-cementing and pozzolanic properties, while most of it is characterized by relatively high content in free lime, sulfates, calcium aluminate and calcium sulfoaluminate compounds [11]. In previews research [12] it has been proven that ettringite is formed and detected in the fly ash mixture one hour after water addition. Moreover, the huge amount of fly ash output (around 11 million tons per year) allows for the selection of fly ash under prescribed limits. Previous experience from the use of this calcareous fly ash in grouts has shown that water retentivity of fly ash-based grouts is very high and the bleeding potential is substantially reduced in comparison to the control mixtures with net cement clinker [13].

EXPERIMENTAL PART

- Materials selection and proportioning

The design of a high-paste-content SCC was based on the recommendations found in the literature [14-16]. The materials selected were cement type CEM I42.5N according to EN 197-1, local HCFA and limestone filler, the characteristics of which are shown in Table 1.

Table 1. Characteristics of the materials used for SCC trial mixes

	Raw material		
Constituents (%)	CEM I42.5N	HCFA	Limestone filler
SiO_2		29.42	3.8
CaO	66.84	41.70	51.3
Al_2O_3	2.40	6.69	1.0
Fe_2O_3	8.11	5.26	0.4
SO_3		3.85	-
MgO	3.91	7.3	1.2
CaO_{free}		10.63	-
K_2O	1.08	0.80	-
Na_2O	0.57	0.38	-
L.O.I.	1.91	8.46	41
Insoluble residue	0.8	9.93	
Fineness (R_{45} retained, %)	1.5	19	
Apparent specific density kg/dm^3	3.14	2.55	2.71
EN 450-1 pozzolanicity index with cement at 28-days (%)	-	85	-

A polycarboxylate-based superplasticizer (PC) was used at a percentage of 1÷2% wt. of cement + fly ash and a viscosity modifying agent (VMA) at a percentage of 0.25% wt. of the total cementitious content passing the 45 μm sieve. A mix of different fragments of crushed limestone aggregates was used based on the gradation of each fragment and Fuller's curve in order to achieve the best packing factor of the aggregate mix as shown in Fig.1.

Many trial mixtures were prepared and tested in order to conclude on the proportioning of the optimum high HCFA volume SCC mixture. Finally, 30% and 50% of the cement quantity was replaced in the test SCC mixtures. The acceptable limits regarding the workability of fresh cement were 500-700 mm expansion in the slump flow test and a passing ability $H_2/H_1 > 0.80$ in the L-box test.

From this preliminary research it was obvious that in order to produce acceptable SCC mixtures with HCFA, higher dosages of PC admixture should be added compared to the control mixture. As indicated in Fig.2, the water demand of CEM I42.5N – HCFA standard consistency pastes increases as the percentage of cement replacement by HCFA is increased in both cases (with and without PC). Therefore, it was decided to add higher dosages of PC into the HCFA SCC mixtures.

Fig. 1. Granulometry of aggregate mix used in all SCC mixtures

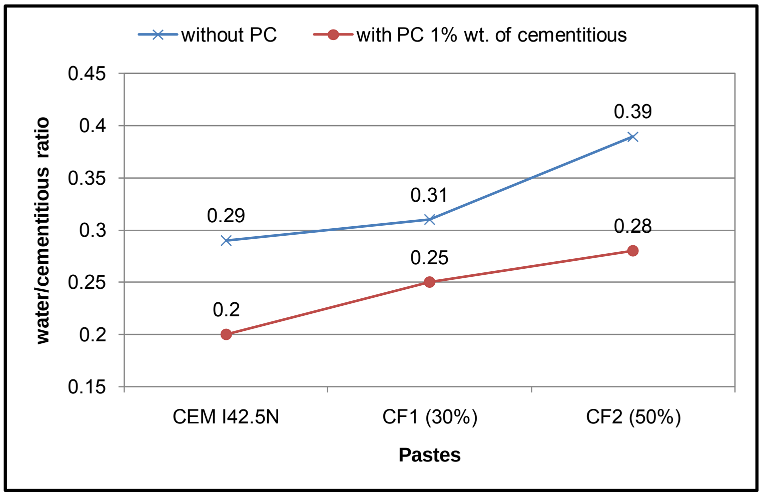

Fig. 2 Water demand of CEM I42.5N-HCFA pastes of standard consistency according to EN 196-3

Amongst the different trial SCC mixtures, only three (control with 100% CEM I42.5N as binder, CF1 and CF2 which had a 30% and 50% wt. cement replacement with HCFA, respectively) were selected and are presented in Table 2.

Table 2. Proportioning of SCC mixtures

Material	Reference (CEM I42.5N)	CF1 (30%)	CF2 (50%)
CEM I 42.5N (kg/m^3)	400	280	200
HCFA (kg/m^3)	-	120	200
Limestone filler (kg/m^3)	160	160	160
w/cementitious ratio	0.45	0.49	0.51
Superplasticizer (% wt. of cementitious)	1.12	1.35	2.0
VMA (% wt. of material <45μm)	0.25	0.25	0.25
Sand 0-4 mm (kg/m^3)	978	978	978
Coarse sand 4-8 (kg/m^3)	326	326	326
Crushed limestone 8-16 mm (kg/m^3)	326	326	326
Workability (flow in mm)	670	560	720
L-box H_2/H_1	0.90	0.85	0.90

- Mixing, specimen preparation and testing

Aggregates were first weighted, then placed into the mixer together with ¼ of the total water quantity and 1 min slow mixing was applied. Afterwards, cement plus fly ash and limestone filler were added together with the water, the PC superplasticizer and VMA. Based on previous experience, PC was added 3 minutes after the addition of water. After proper mixing the measurements of slump flow test and L-box were carried out (Table 3).
The SCC mixtures were cast in specimens; cubes (15x15x15 cm), cylinders (15x30 cm) and prisms (10x10x40 cm) which, after demoulding, were cured in a climatic chamber (95% RH and 20°C temperature). Compressive strength, modulus of rupture and splitting tensile strength were measured, as well as the elastic modulus of concrete, based on stress-strain diagrams. The dynamic modulus of elasticity was also estimated, based on ultrasonic pulse velocity measurements. The results are shown in Tables 4 and 5.

Table 3. Properties of fresh SCC mixtures

SCC mixture	Slump flow test					L-box test	
	d1 (mm)	d2 (mm)	d3 (mm)	T_{500mm} (s)	T_{final} (s)	H_2/H_1	T (s)
Control	650	670	680	4	24	0.90	3
CF1 (30%)	570	560	540	10	33	0.85	10
CF2 (50%)	700	740	720	5	29	0.90	5

Table 4. Mechanical and elastic properties of SCC mixtures

Properties\Concrete Mixtures	Control (CEM I42.5N)	CF1 (30%)	CF2 (50%)
28-d cube/28-d cylinder Compressive strength (MPa)	47.37/40.65	46.50/34.50	49.91/38.58
28-d Modulus of rupture (MPa)	7.80	7.00	7.45
28-d Splitting tensile strength (MPa)	2.08	1.91	2.02
28-d Elastic modulus (GPa)	36.91	36.22	39.61
Calculated 28-d elastic modulus (GPa)*	34.31	32.43	33.72
28-d Dynamic modulus of elasticity (GPa)	54.03	52.81	55.13

*values calculated based on cylindrical compressive strength according to the CEB-FIP Model Code $E_{c28} = 2.15 \times 10(f_{cm}/10)^{1/3}$

Table 5. Rate of strength development of SCC mixtures

Properties\Concrete Mixtures	Control (CEM I42.5N)	CF1 (30%)	CF2 (50%)
Cubic 7-d compressive strength (MPa)	40.80	39.61	36.46
Cubic 28-d compressive strength (MPa)	47.37	46.50	49.90
Increase (%)	16.1	17.4	36.9

A number of prisms were placed after demoulding in a conditioned chamber with 50% RH and 20°C temperature in order to measure free shrinkage deformations using displacement transducers (LVDTs) attached on the specimens and connected to a data logger. Two prisms from each SCC mixture were fully wrapped in membrane in order to measure autogenous shrinkage. The early shrinkage deformations in microstrain measured for both wrapped and exposed specimens have been plotted in Figs. 3 and 4.

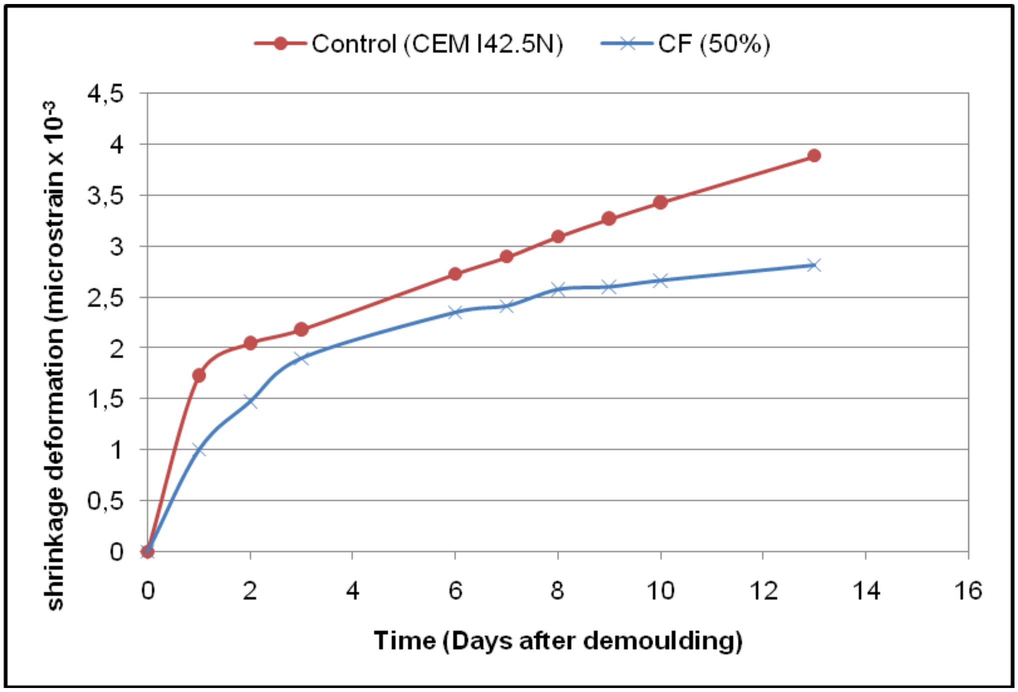

Fig. 3 Early shrinkage deformations of SCC mixtures at 20°C and 50÷60% RH

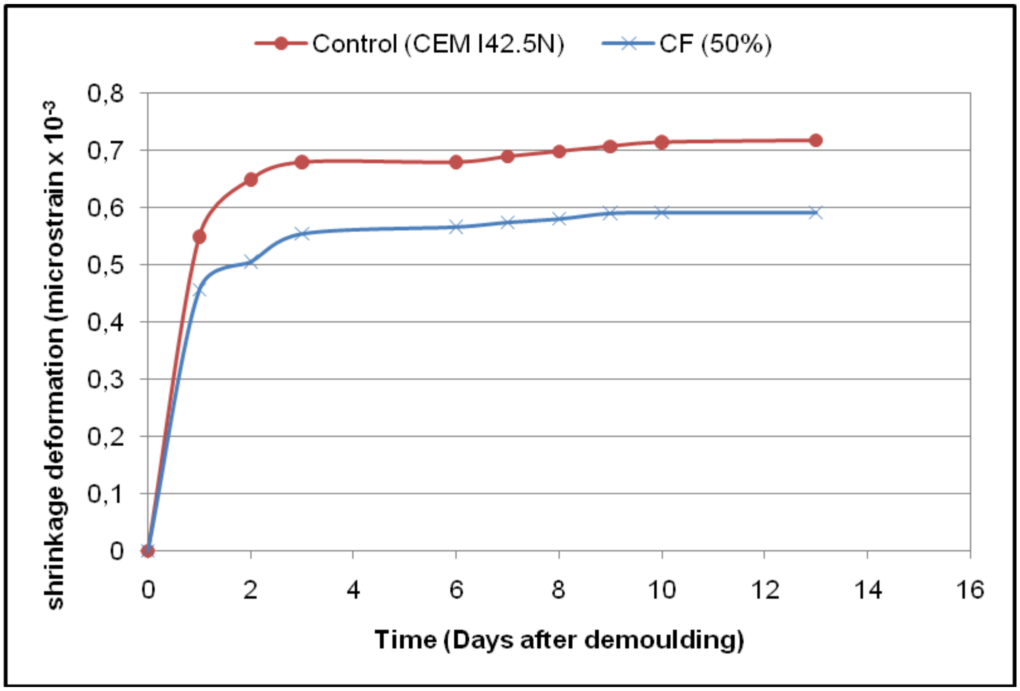

Fig. 4 Early shrinkage deformations of wrapped SCC specimens at 20°C

RESULTS AND DISCUSSION

A 28-d compressive strength of about 50 MPa has been achieved with a 50% cement replacement by HCFA, keeping a low water to cementitious ratio (0.51) by using almost a 2% wt. of cementitious dosage of PC superplasticizer. The 7-day compressive strength of this SCC mixture corresponds to 72% of the 28-day strength. The CF1 SCC mixture with 30% of the total cementitious material HCFA has developed 28-day compressive strength comparable to that of the control mixture (46-50 MPa), by keeping the water to cementitious ratio equal to 0.49 and also by increasing the PC superplasticizer dosage by 20%. However, the rheological characteristics of the fresh mixture were barely acceptable and a higher dosage of PC should be added.

Early shrinkage deformations of HCFA SCC mixtures are clearly lower than those of the control mixture. Autogenous shrinkage measured in the case of wrapped specimens was also lower in HCFA mixtures. This behavior of HCFA SCC mixtures is considered to be related to the constituents of HCFA, reacting as expanding agents for the period from demoulding until hardening.

CONCLUSIONS

Research on the use of HCFA as supplementary material in SCC mixtures is very limited and according to the results of this research work it seems that a selected HCFA may replace high volume of cement in such mixtures. The extra water demand due to the incorporation of HCFA in the mixture can be confronted by increasing the superplasticizer dosage, while the very low price of HCFA (about 5% of the cement price) allows for such modifications of the SCC proportioning or for the improvement of HCFA quality. Thus, adequate fluidity without segregation may be achieved in fresh mixtures. Also, the compressive strength of the hardened SCC with 50/50 CEM I42.5N/HCFA as cementitious material (about 50 MPa) is comparable to that of the control mixture, while the other mechanical and elastic properties measured were also sufficient. Furthermore, the incorporation of HCFA in SCC mixtures seems to reduce early shrinkage deformations (autogenous and plastic). Consequently, the production of high volume HCFA self compacting concrete seems feasible and technically advantageous.

ACKNOWLEDGEMENTS

The authors would like to thank, amongst other students, A. Bouras and G. Tzovaras for their assistance in the completion of the research program.

REFERENCES

[1] Hwang D. and Khayat K.H. "Effect of Mixture Composition on Restrained Shrinkage Cracking of Self Compacted Concrete Used in Repairs", ACI Materials Journal, 2008, 105, pp. 499-510.
[2] Vikan H., Hammer T.A. and Kjellsen K.O. "Drying Shrinkage of SCC – Influence of Ternary Composite Cements" In Design, Production and Placement of Self-Consolidating Concrete: Proceedings of SCC2010 RILEM Conference, Montreal, Canada, September 26-29, 2010 (Eds K.H. Khayat and D. Feys) Springer, New York, 2010, pp. 271-281.
[3] EURACOAL E.U. Statistics 2007/2008, www.euracoal.com accessed on 01/04/2011.
[4] Papayianni I. "Performance of a High Content in Lime and Sulfates Fly Ash in Roller Compacted Concrete" in ACI SP-132 (Ed V.M. Malhotra V.M.), ACI, Detroit, 1992, pp. 367-386.
[5] Papayianni I., Tsimas S. and Moutsatsou A. "Standardization Aspects Concerning HCFA(s)" in Proceedings of the 2009 WOCA Conference, May 4-7, 2009, Lexington Kentucky, available at www.flyash.info
[6] Lura P., Pease B, Mazzotta G.B., Rajabipour F. and Weiss J. "Influence of Shrinkage Reducing Admixtures on Development of Plastic Shrinkage Cracks", ACI Materials Journal, 2007, 104, pp. 191-193.
[7] Collepardi M. "The New Concrete" Treviso, Graffiche Tintoretto, 2006, pp. 240-243.
[8] Collepardi M. "The New Concrete" Treviso, Graffiche Tintoretto, 2006, pp. 347-355.
[9] Collepardi M., Borsoi A., Olagot J.J.O. and Troli R. "Effects of SRA in shrinkage compensating concretes" Cement and Concrete Composites, 2005, 27, pp. 704-708.
[10] Moisiadis S. and Papayianni I. "Influence of SAP(s) on Water Release and Early Deformation of SCC Mixtures" In Design, Production and Placement of Self-Consolidating Concrete: Proceedings of SCC2010 RILEM Conference, Montreal, Canada, September 26-29, 2010 (Eds K.H. Khayat and D. Feys) Springer, New York, 2010, pp. 303-309.

[11] Papayianni I. “Use of calcareous ash in civil engineering”. Presented in EUROCOALASH Conference, Copenhagen, Denmark, May 27-28, 2010.
[12] Papayianni J. “An investigation on the pozzolanicity and hydraulic reactivity of a High-Calcium Fly Ash” Magazine of Concrete Research, 1987, 39, pp. 19-28.
[13] Papayianni J. “High-Calcium Fly Ash Grouts”, In: Concrete 2000, Economic and Durable Construction through excellence Volume Two (Eds R.K. Dhir and M.R. Jones), E and FN SPON, 1994, pp. 1305-1312.
[14] Okamura H. “Self-Compacting Concrete” ACI Concrete International, 1997, 19, pp. 50-54.
[15] Lemieux G, Hwang D. and Khayat K.H. “Effect of Material Constituents and Mix Design on Performance of SCC for Precast, Prestressed Girders” In Design, Production and Placement of Self-Consolidating Concrete: Proceedings of SCC2010 RILEM Conference, Montreal, Canada, September 26-29, 2010 (Eds K.H. Khayat and D. Feys) Springer, New York, 2010, pp. 25-35.
[16] RILEM “Specifications and Guidelines for Self Compacted Concrete” accessed online on 01/04/2011 (http://www.efnarc.org/)